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Trilinear Gauge Couplings from $\gamma\gamma \to W^+W^-$

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If there is no the Standard Model Higgs boson, the interaction among the gauge bosons becomes strong at high energies ($\sim 1\,\mathrm{TeV}$). The effects of strong electroweak symmetry breaking could manifest themselves indirectly through the vertices as anomalous gauge boson couplings before they give rise to new physical states like resonances. Here a study of the measurement of trilinear gauge couplings κ_γ and λ_γ is presented looking at the hadronic decay channel of the WW boson pair at an $\gamma\gamma$ - collider. A sensitivity of $\mathcal{O}(10^{-3} - 10^{-4})$ can be reached depending on the coupling under consideration and on the initial polarisation state.

1. INTRODUCTION

Deviations of the triple gauge boson couplings (TGCs) from their values predicted by the Standard Model (SM) are a possible indication for new physics (NP) beyond the SM. If no light Higgs boson exists the mechanism responsible for the restoring the unitarity could well be the strong electroweak symmetry breaking (SEWSB) mechanism [1]. As a consequence, at energies below NP cut-off scale Λ_{NP}[1] the effects of NP are reflected in the TGC's values leading to their deviations $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ from the SM predictions. Since these deviations decrease as Λ_{NP} increases, their observation requires a very precise measurements, more precise than those at LEP and Tevatron. With a high event statistics at a $\gamma\gamma$ collider option at the International Linear Collider (ILC) it is possible to reach a high precision of the TGC measurements.

Anomalous TGCs affect both the total production cross-section and the shape of the differential cross-section as a function of the W production angle. As a consequence, distributions of W decay products are changed also. Thus, the information about TGCs can be extracted from the angular distributions of the reconstructed W boson. In $\gamma\gamma$ collisions the TGCs contribute through t-channel W-exchange.

In this study the expected sensitivity for a measurement of the couplings κ_γ and λ_γ in $\gamma\gamma \to W^+W^- \to$ 4jets at $\sqrt{s_{ee}} = 500\,\mathrm{GeV}$ ($\sqrt{s_{\gamma\gamma}} \leq 400\,\mathrm{GeV}$) is investigated. There are two possible initial $\gamma\gamma$ helicity states depending on the photon handedness, denoted as $J_Z = 0$ (if two photons have the same helicities) and $|J_Z| = 2$ (if two photons have the opposite helicities). Total and differential cross-sections distributions as a function of the anomalous TGCs ($\Delta\kappa_\gamma, \Delta\lambda_\gamma \neq 0$), simulated with the tree-level Monte Carlo (MC) generator WHIZARD [2], for all possible initial and final state helicity combinations are shown in Figures 1 and 2.

2. SIGNAL AND BACKGROUND SIMULATION

As a beam simulation CIRCE2 [3] is used to describe realistic beam spectra for $\gamma\gamma$-colliders. The response of a detector has been simulated with SIMDET V4 [4], a parametric Monte Carlo for the TESLA e^+e^--detector. It includes a tracking and calorimeter simulation and a reconstruction of energy-flow-objects (EFO)[2]. Only the EFOs with a polar angle above 7° are taken for the W boson reconstruction, simulating the acceptance of the photon collider detector as the only difference to the e^+e^--detector [5]. The signal and background events are studied on a sample of events generated with WHIZARD and overlayed with low energy $\gamma\gamma \to$hadrons events (*pileup*) [6]. The

[1] $\Lambda_{NP} \sim 4\pi v \approx 3\,\mathrm{TeV}$
[2] Electrons, photons, muons, charged and neutral hadrons and unresolved clusters that deposit energy in the calorimeters.

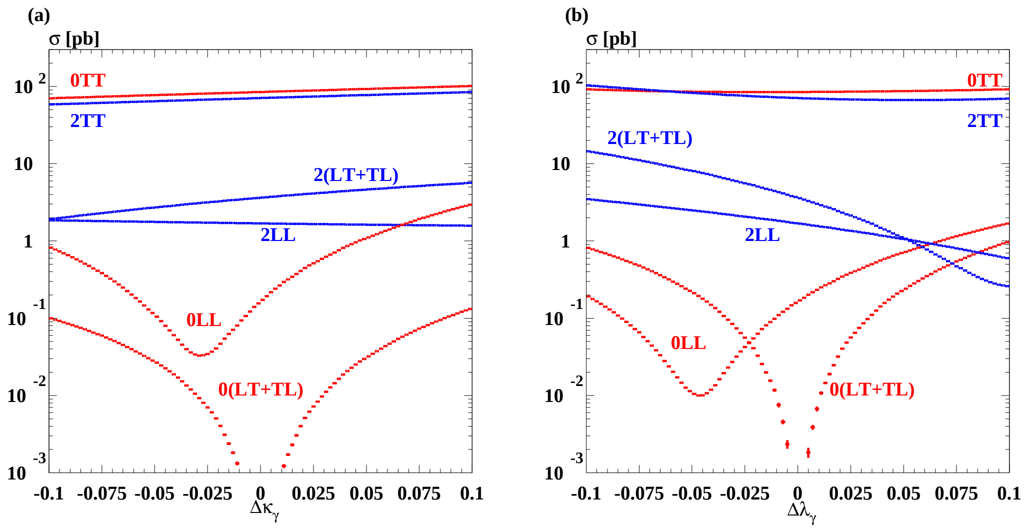

Figure 1: Contribution of different WW helicity states for $J_Z = 0$ and $|J_Z| = 2$ states in the presence of anomalous couplings (a): κ_γ and (b): λ_γ at $\sqrt{s_{\gamma\gamma}} = 400$ GeV, assuming fully polarised photon beams. The deviations are denoted as $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$. The initial photon state $J_Z = 0$ is denoted with "0" in front of helicity labelling $(LL, TT, (LT + TL))$ while the state $|J_Z| = 2$ is denoted with "2". TT=(±±) for $J_Z = 0$ and TT=(±±)+(±∓) for $|J_Z| = 2$. LT+TL=(±0)+(0±) and LL=(00).

corresponding number of added pileup events per bunch crossing is 1.8 [7]. The informations about the neutral particles (*neutrals*) from calorimeter and charged tracks (*tracks*) from tracking detector are used to reconstruct the signal and background events. The potential background for both initial J_Z states are $\gamma\gamma \to q\bar{q}$ events that can mimic the signal with four jets when gluons are radiated in the final state. The QCD corrections to the $q\bar{q}$-pair Born level production cross-section are different for the two J_Z states: in the $|J_Z| = 2$ state the corrected cross-section is $\sigma_2^{QCD} \sim \sigma_2^{Born}(1 + k\alpha_s/\pi)$ with k being of $\mathcal{O}(1)$, resulting in a Born cross-section correction of 4-5%. In this study this correction is not taken into account. In the $J_Z = 0$ state, the suppression factor (m_f^2/s) [8] leads to a Born level cross-section close to zero but the QCD corrections lead to an enhancement by double-logarithmic terms $\sim (\alpha_s \log^2(s/m_q^2))^n$ [9]. To estimate the corrected cross-section for the $J_Z = 0$ state the $\mathcal{O}(\alpha_s^2)$ diagrams are taken into account i.e. the diagrams contributing to $\gamma\gamma \to q\bar{q}gg$ and $\gamma\gamma \to q\bar{q}(g \to)q\bar{q}$. The y_{cut} cut parameter $((p_a + p_b)^2 > sy_{cut};\ a, b = q, \bar{q}, g/q, g/\bar{q})$ for a variable centre-of-mass energy s is defined by generating only events with the invariant masses of each parton pair above 30 GeV resulting in an emission of hard gluons. The signal events for both J_Z states and background events for the $|J_Z| = 2$ state are generated with O'Mega matrix element generator [10] taking into account only the lowest order Feynman diagrams. The QCD correction for the $q\bar{q}$ pair production in the $J_Z = 0$ state is estimated generating the background events with MadGraph [11].

2.1. Energy Flow and Event Selection

In order to minimise the pileup contribution to the high energy signal tracks, the information on the track impact parameters is used in the same way as in the case of γe-collisions [12] allowing the rejection of $\sim 60\%$ of pileup tracks and $\sim 10 - 15\%$ of signal tracks. The remaining tracks are combined into four jets and the events with a number of EFO greater than 40 and number of charged tracks greater than 20 are accepted only. The two reconstructed W bosons are denoted as forward ($\cos\theta > 0$, W_F) and backward ($\cos\theta < 0$, W_B) where θ is a W boson production angle in the centre-of-mass system (CMS). The angle between the two jets belonging to the same W boson, boosted to the CMS, is used as a next selection criteria - if the angle is within a given range of $40° < \theta < 140°$, the event is accepted. Further, events with a total mass above 125 GeV and the individual W boson mass of $60\text{GeV} < M_W < 100\text{GeV}$ are accepted. That results in efficiencies of approximately 53% for signal and less than 2% for background events i.e. in a purity of 81% in both J_Z states. The top pair production is estimated to be negligible. The final angular

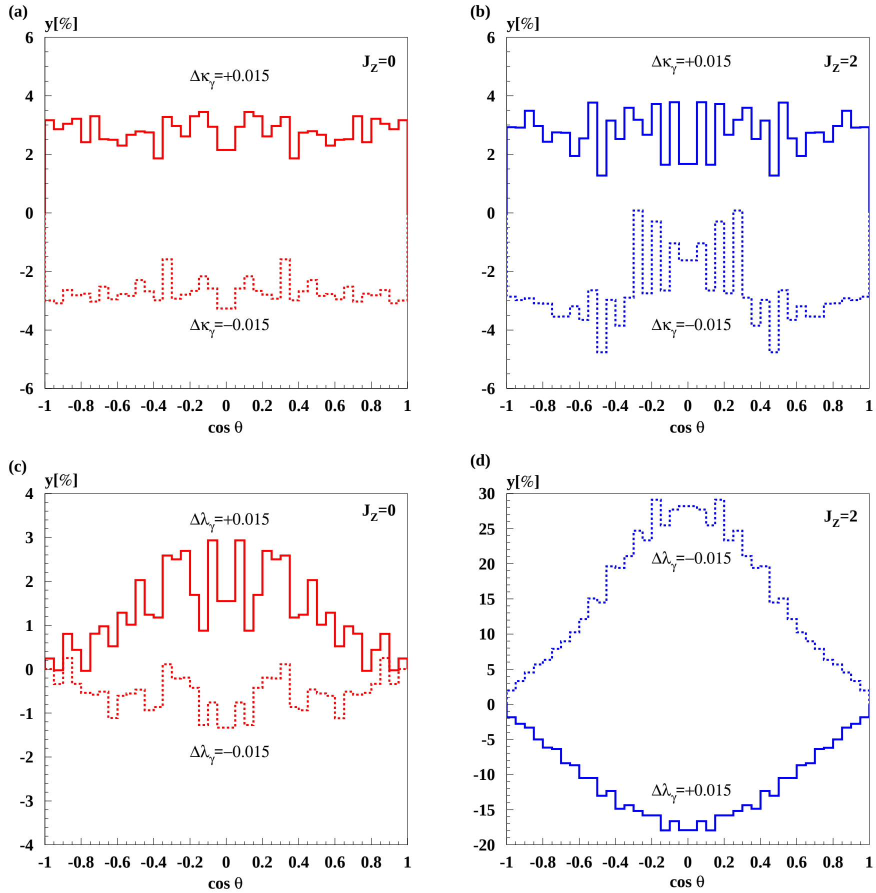

Figure 2: Relative deviations of differential cross-section from the SM predictions in presence of anomalous coupling (a): $\kappa_\gamma = \pm 1.015$ in the $J_Z = 0$ state $(\Delta\lambda_\gamma = 0)$, (b): $\kappa_\gamma = \pm 1.015$ in the $|J_Z| = 2$ state $(\Delta\lambda_\gamma = 0)$, (c): $\lambda_\gamma = \pm 0.015$ in the $J_Z = 0$ state $(\Delta\kappa_\gamma = 0)$ and (d): $\lambda_\gamma = \pm 0.015$ in the $|J_Z| = 2$ state $(\Delta\kappa_\gamma = 0)$, at $\sqrt{s_{\gamma\gamma}} = 400$ GeV, assuming fully polarised photon beams. Solid lines correspond to $\Delta\kappa_\gamma, \Delta\lambda_\gamma = +0.015$ and dotted lines correspond to $\Delta\kappa_\gamma, \Delta\lambda_\gamma = -0.015$. All WW helicity combinations are included. $y[\%] = \frac{[d\sigma_{TOT}^{AC} - d\sigma_{TOT}^{SM}]}{d\sigma_{TOT}^{SM}}$.

distributions for the $|J_Z| = 2$ state[3] used for the TGCs error estimation are shown in Figure 3.

3. FIT METHOD AND ERROR ESTIMATIONS

For the extraction of the TGSs from the reconstructed kinematical variables (Fig. 3) a binned Likelihood fit is used. A sample of $2 \cdot 10^6$ SM signal events is generated with WHIZARD and passed trough the detector simulation. Each event is described reconstructing five kinematical variables - the W production angle with respect to the e^- beam direction θ, the W's polar decay angles $\theta_{1,2}$ (angle of the fermion with respect to the W flight direction measured in the W rest frame) and the azimuthal decay angles $\phi_{1,2}$ of the fermion with respect to a plane defined by W and the beam axis. In hadronic W-decays the up- and down-type quarks cannot be separated so that only $|cos\theta_{1,2}|$ is measured. The matrix element calculations from WHIZARD are used to obtain weights [12] to reweight the angular distributions as functions of the anomalous TGCs where $\Delta\kappa_\gamma$ and λ_γ are the free parameters. Six-dimensional (6D)

[3]The similar angular distributions are obtained for the $J_Z = 0$ state.

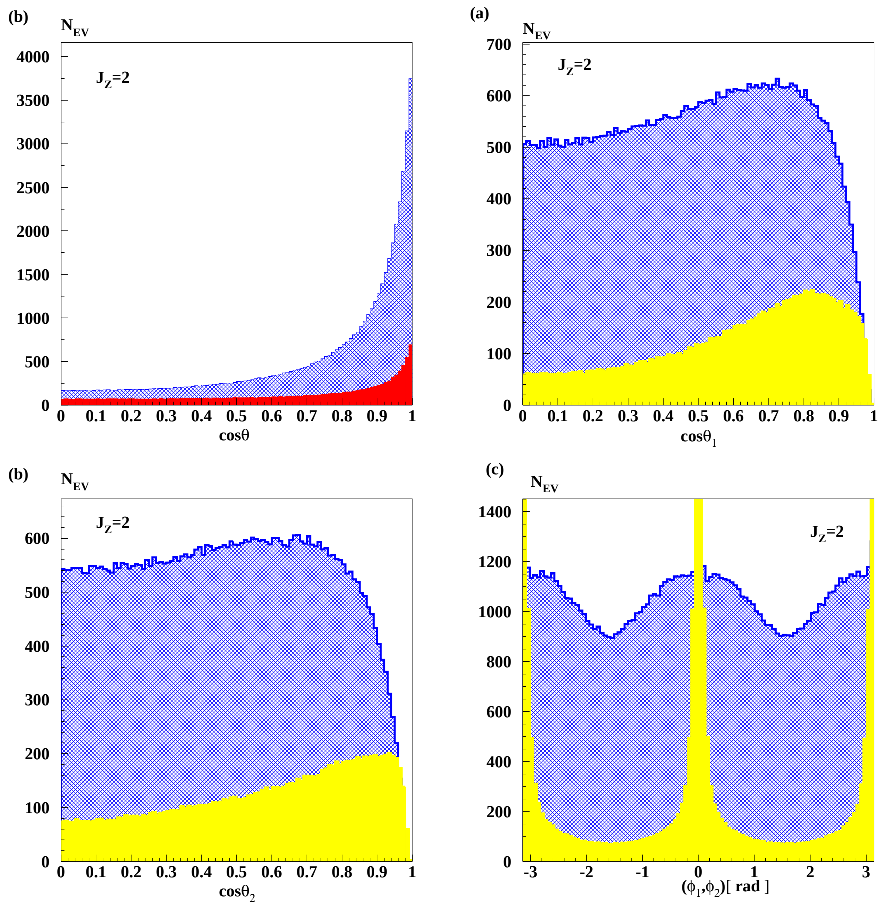

Figure 3: Angular distributions of signal (blue) and background (red, yellow) events after the detector simulation used in the fit in the $|J_Z| = 2$ state over (a): the decay angle $\cos\theta_1$ of W_F (b): the decay angle $\cos\theta_2$ of W_B (c): the azimuthal angle (ϕ_1, ϕ_2).

event distributions over $\cos\theta$, $\cos\theta_{1,2}$, $\phi_{1,2}$ and centre-of-mass energy are fitted with MINUIT [13], minimising the Likelihood function depending on κ_γ and λ_γ:

$$\begin{aligned}\mathcal{L} \;=\; -&\sum_{i,j,k,l,m,p} \left[z \cdot N^{SM}(i,j,k,l,m,p) \cdot \log\left(z \cdot n \cdot N^{\Delta\kappa_\gamma,\Delta\lambda_\gamma}(i,j,k,l,m,p)\right)\right. \\ &\left. - z \cdot n \cdot N^{\Delta\kappa_\gamma,\Delta\lambda_\gamma}(i,j,k,l,m,p)\right] + \frac{(n-1)^2}{2(\Delta L^2)},\end{aligned}$$

where i,j,k,l and m run over the reconstructed angular distributions $\cos\theta, \cos\theta_{1,2}$ and $\phi_{1,2}$, p runs over the reconstructed centre-of-mass energy, $N^{SM}(i,j,k,l,m,p)$ is the "data" which corresponds to the SM MC sample, $N^{\Delta\kappa_\gamma\Delta\lambda_\gamma}(i,\, j,\, k,\, l,\, m,\, p)$ (MC sample) is the event distribution weighted by the function $R(\Delta\kappa_\gamma,\Delta\lambda_\gamma)$ and $\sigma(i,\, j,\, k,\, l,\, m,\, p) = \sqrt{N^{SM}(i,j,k,l,m,p)}$. The factor z sets the number of signal events to the expected one after one year of running of an $\gamma\gamma$-collider. In case where the background is included in the fit z defines the sum of signal and background events and $n \cdot N^{\Delta\kappa_\gamma,\Delta\lambda_\gamma} \to [n \cdot N^{\Delta\kappa_\gamma,\Delta\lambda_\gamma}_{signal} + N_{bck}]$. The number of background events is normalised to the effective W boson production cross-section in order to obtain the corresponding number of background events after one year of running of an $\gamma\gamma$-collider for corresponding J_Z state. It is assumed that the total normalisation (efficiency, luminosity, electron polarisation) is only known with a relative uncertainty ΔL. Thus, n is taken as a free parameter in the fit and constrained to unity with the assumed normalisation uncertainty. Per construction the fit is bias-free and thus returns always exactly the SM as central values. In the $|J_Z| = 2$ state $\Delta L = 0.1\%$ is a realistic

precision that can be achieved while for the $J_Z = 0$ due to the small number of events[4], the luminosity is expected to be measured with an error of $\Delta L = 1\%$.

Table I shows the estimated statistical errors we expect for the different couplings at $\sqrt{s_{ee}} = 500\,\mathrm{GeV}$ for a two-parameter[5] 6D fit at detector level including the pileup and background events in both J_Z states.

1000 fb^{-1}	without pileup			with pileup			pileup+background		
6D fit	$J_Z = 0/\lvert J_Z\rvert = 2$			$J_Z = 0/\lvert J_Z\rvert = 2$			$J_Z = 0/\lvert J_Z\rvert = 2$		
ΔL	1%	0.1%	0	1%	0.1%	0	1%	0.1%	0
$\Delta\kappa_\gamma \cdot 10^{-4}$	19.9/29.9	5.5/6.2	2.6/3.7	26.9/37.4	5.8/6.8	3.0/4.6	27.8/37.8	5.9/7.0	3.1/4.8
$\Delta\lambda_\gamma \cdot 10^{-4}$	3.7/3.1	3.7/3.1	3.7/3.1	5.4/4.6	5.2/4.6	5.2/4.6	5.7/4.8	5.6/4.8	5.6/4.8

Table I: Estimated statistical errors for κ_γ and λ_γ from the 6D fit at detector level for both J_Z states in $\gamma\gamma$ collisions at $\sqrt{s_{ee}} = 500$ GeV, without pileup, with pileup and with background events.

In Table II the results for $\sqrt{s_{\gamma\gamma}} = 400\,\mathrm{GeV}$ and $\sqrt{s_{\gamma\gamma}} = 400\,\mathrm{GeV}$ are compared using a fixed photon energy.

110 fb^{-1}	$\sqrt{s_{\gamma\gamma}} = 400$ GeV						$\sqrt{s_{\gamma\gamma}} = 800$ GeV					
5D fit	$J_Z = 0$			$\lvert J_Z\rvert = 2$			$J_Z = 0$			$\lvert J_Z\rvert = 2$		
ΔL	1%	0.1%	0	1%	0.1%	0	1%	0.1%	0	1%	0.1%	0
$\Delta\kappa_\gamma \cdot 10^{-4}$	14.4	5.4	2.6	20.1	6.2	3.8	7.2	4.5	2.4	8.1	4.6	2.6
$\Delta\lambda_\gamma \cdot 10^{-4}$	3.0	3.0	3.0	1.6	1.6	1.6	1.3	1.3	1.3	0.63	0.58	0.56

Table II: Estimated statistical errors for κ_γ and λ_γ from the five-dimensional (5D) two-parameter fit at generator level for the $J_Z = 0$ and $|J_Z| = 2$ at $\gamma\gamma$ collisions at $\sqrt{s_{\gamma\gamma}} = 400$ and 800 GeV. The number of events for both $J_Z = 0$ states is normalised to the expected one with integrated luminosity of 110 fb^{-1} in the high energy peak.

The comparison of κ_γ and λ_γ obtained from $e^+e^-, \gamma e$ and $\gamma\gamma$ at $\sqrt{s_{ee}} = 500$ GeV is shown in Table III (left side). The right side of Table III shows the comparison at $\sqrt{s_{e^+e^-,\gamma\gamma}} = 800$ GeV for the two types of collider. The sensitivities to κ_γ and λ_γ in $\gamma\gamma \to W^+W^-$ at $\sqrt{s_{\gamma\gamma}} = 800$ GeV, including the variable energy spectrum, background and pileup events are approximated scaling the estimated sensitivities at generator level (Table II) by a factor obtained for $\sqrt{s_{ee}} = 500$ GeV. The sensitivities at an e^+e^--collider are estimated at generator level.

	$\sqrt{s_{ee}} = 500$ GeV					$\sqrt{s_{\gamma\gamma,e^+e^-}} = 800$ GeV		
LEFT	γe	$\gamma\gamma$		e^+e^-	RIGHT	$\gamma\gamma$		e^+e^-
Mode	Real/Parasitic $\lvert J_Z\rvert = 3/2$	$\lvert J_Z\rvert = 2$	$J_Z = 0$	$\lvert J_Z\rvert = 1$	Mode	$\lvert J_Z\rvert = 2$	$J_Z = 0$	$\lvert J_Z\rvert = 1$
$\int \mathcal{L}\Delta t$	160 fb^{-1}/230 fb^{-1}	1000 fb^{-1}		500 fb^{-1}	$\int \mathcal{L}\Delta t$	1000 fb^{-1}		
ΔL	0.1%	0.1%	1%	-	ΔL	0.1%	1%	-
$\Delta\kappa_\gamma \cdot 10^{-4}$	10.0/11.0	7.0	27.8	3.6*	$\Delta\kappa_\gamma \cdot 10^{-4}$	5.2	13.9	2.1*
$\Delta\lambda_\gamma \cdot 10^{-4}$	4.9/6.7	4.8	5.7	11.0*	$\Delta\lambda_\gamma \cdot 10^{-4}$	1.7	2.5	3.3*

Table III: *Left*: Comparison of the κ_γ and λ_γ sensitivities at γe-, $\gamma\gamma$- and e^+e^--colliders estimated at $\sqrt{s_{ee}} = 500$ GeV using the polarised beams. In case of photon colliders, the background and the pileup are included. (*) denotes the estimation at the generator level. *Right*: Comparison of the κ_γ and λ_γ sensitivities at $\gamma\gamma$- and e^+e^--colliders estimated at $\sqrt{s_{e^+e^-,\gamma\gamma}} = 800$ GeV using the polarised beams. (*) denotes the estimation at the generator level. The sensitivities at $\gamma\gamma$-collider are scaled for the background, pileup and the energy spectrum.

[4]It is assumed that the luminosity will be measured counting the events produced in $\gamma\gamma \to l^+l^-$ where the cross-section is m^2/s suppressed.

[5]A two-parameter fit means that both couplings are allowed to vary freely as well as the normalisation n.

Concerning the systematic errors the influence of the background and the degree of photon polarisation have been investigated, assuming $\Delta L = 0.1\%$ in the $|J_Z| = 2$ state and $\Delta L = 1\%$ in the $J_Z = 0$ state. In the $J_Z = 0$ state, the polarisation uncertainty of 0.0021 for κ_γ is to less than the statistical error while in the $|J_Z| = 2$ state, the polarisation uncertainty of 0.0018 for κ_γ is less than three times the statistical error. The uncertainty on λ_γ in both J_Z states is found to be negligible. In the $|J_Z| = 2$ state the background cross-section should be known to better than 0.8% for κ_γ and to better than 4% for λ_γ if the corresponding systematic uncertainty should no be larger than the statistical error. For $J_Z = 0$ the requirement is 0.6% for λ_γ while there are basically no restrictions for κ_γ.

4. CONCLUSIONS

The estimated sensitivity of the TGCs measurement in both $\gamma\gamma$ initial states at $\sqrt{s_{ee}} = 500$ GeV with integrated luminosities of $\mathcal{L}_{\gamma\gamma} \approx 1000$ fb^{-1} is of order $\approx 7 \cdot 10^{-4}$ for $\Delta\kappa_\gamma$ and higher than $5 \cdot 10^{-4}$ for $\Delta\lambda_\gamma$ in the $|J_Z| = 2$ state assuming $\Delta L/L \approx 10^{-3}$. The state $J_Z = 0$ takes into account a larger error on the luminosity measurement of $\Delta L/L \approx 10^{-2}$ resulting in a sensitivity to κ_γ higher than $3 \cdot 10^{-3}$ and to λ_γ higher than $6 \cdot 10^{-4}$. While κ_γ can be measured somewhat better in e^+e^-, the $\gamma\gamma$-collider provides a higher accuracy for a λ_γ measurement compared to the e^+e^-- and γe-colliders.

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